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BASIC RESEARCH on AURORA and AIRGLOW

D.M. Hunten and A. Vallance Jones

University of Saskatchewan, Department of Physics, Saskatoon,
Canada

Contract No. AF19(604)-7265

Project No. 7661

Task No. 76612

FINAL REPORT FRC

April 30th, 1963

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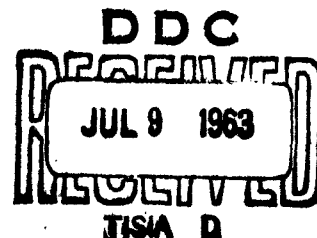Canada

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CONTENTS

1. ABSTRACT

The principal instruments and facilities available for work
under the Contract are described with special emphasis on new
construction or modifications. This equipment includes two high
dispersion grating spectrographs, two types of patrol spectrographs,
ground-based, aircraft-borne and balloon-borne infrared spectrometers,
a scanning spectrometer for the visible and ultraviolet regions
with memory unit, two types of photometer for the study of twilight
alkali emissions, a Michelson interferometer for the near infrared
region and a temperature-measuring photometer for the measuring of
auroral rotational temperatures. Also described are facilities for
producing specialized interference filters, a source for the
Vegard-Kaplan bands, intensity standards for absolute brightness
measurements of aurora and a system for obtaining all-sky photographs
through interference filters. There is also a brief description
of two rocket-borne photometers which are under development.

Abstracts of Scientific Reports and theses produced under the
Contract are reprinted. The twilight airglow and dayglow measure-
ments, observations of auroral emissions, of the night airglow and
of auroral temperatures are discussed. Among the most notable
results are the determination of the vertical distributions of
sodium, potassium and lithium from the twilight observations, the
discovery of a seasonal variation in the infrared atmospheric
oxygen bands in the twilight, the observation of the dayglow in
the infrared atmospheric oxygen bands and important conclusions
as to the production and distribution of N_2^+ ions in the upper
atmosphere from twilight observations. The twilight observations
of lithium clearly show the effects of high altitude nuclear

explosions. A study is described of the possibility of measuring atmospheric temperatures using the vibrational ratios of N_2^+ bands. New quantitative measurements of the Vegard-Kaplan bands in the second positive bands of N_2 with the photoelectric scanning spectrometer and memory are described, as well as an important laboratory study of the transition moment of the Vegard-Kaplan bands. The results of the patrol spectrograph study of the hydrogen emissions are reported. Refined methods of measuring the temperature distribution in the upper atmosphere from the rotational fine structure of the N_2^+ bands are described; these methods make it possible to construct a temperature profile for the atmosphere from 95 to 170 km.

General conclusions and proposals for further work are presented.

Chapter 2.   INTRODUCTION

Research carried out in the period from 1960 to 1963 is described in this report. Chapter 3 lists the principal items of equipment available for work on the contract with some descriptive material on newly designed or modified apparatus. Chapters 4 to 7 summarize the results in the different projects which are in progress or have been completed. In these chapters reference is made to Chapter 8 which comprises abstracts of all the scientific reports produced under the contract and of all the theses written by students receiving some support. Naturally the detailed discussions of individual investigations are to be found in the original scientific reports which for the most part have been published in recognized scientific journals. This Final Report however provides a general description and guide to this work.

Since this is a continuation of the work done under Contracts AF19(602)-152 and AF19(604)-1831 it may sometimes be useful to read the Final Reports of these contracts in conjunction with this Report. The Final Reports of the former Contracts will be referred to as FRA and FRB respectively.

In Chapter 10 are summarized some general conclusions and ideas about the further development of research on the aurora and airglow at the Institute of Upper Atmospheric Physics.

Chapter 3.   EQUIPMENT

Since many items of equipment have not been substantially
modified since the final reports* of the previous contracts
were written, this section will give a detailed description of
new or modified equipment only. Details of instruments listed
here briefly may be found in reports FRA and FRB*.

3.1 Grating spectrographs

The 5-in. and the 9-in. grating spectrographs have
not been modified since FRB was written. It is planned in the
near future to modify the 5-in. spectrograph to make accurate
measurements of relative brightnesses of auroral features by
adding to it a lower dispersion grating spectrograph covering
the entire region between 4000 and 7000 $\overset{o}{A}$. Both spectrographs
will make simultaneous exposures, with the same field of view.
A grating, blazed at 1.6 μ, will be used in the 5-in. instrument
to obtain better dispersion in the red region which will be
studied in the second order.

3.2 Patrol spectrographs

Two Perkin-Elmer patrol spectrographs are at our
disposal. One has been operated at Meanook, north of Edmonton
and the other at Saskatoon. These instruments have been
converted to a timed exposure program.

The 2-in. fast patrol spectrograph has been rebuilt
according to the design of Clark and Romick[†]. A similar instrument

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*FRA is the final report under contract AF19(604)-152 and FRB is
 the final report under Contract AF19(604)-1831.

[†]J. Optical Soc. Amer., __49__, 141 (1959).

has been constructed for use at Churchill and another will be situated at Flin Flon. These spectrographs use 16 mm film and are capable of obtaining good auroral spectra in 5 min.

3.3 Infrared spectrometers

The 1.0 to 2.0 μ spectrometer, IR1, remains substantially unchanged. The germanium detector has been replaced by an immersed PbS cooled detector and the grating which was blazed at 1.0 μ has been replaced by one blazed at 1.6 μ. The change of grating has increased the efficiency in the 1.5 μ region where much of the work with this instrument has been done.

The second grating spectrometer IR2 originally constructed for observations beyond 2.0 μ has also been converted to work in the 1.0 to 2.0 μ region with a grating blazed at 1.6 μ. This instrument has been modified for high altitude observations from a KC-135 aircraft.

The balloon-borne spectrometer, fully described in CR-6 was eventually recovered after its flight and is still in good condition.

3.4 Photoelectric Grating Spectrometer

This instrument has been in use for over ten years; from time to time modifications have been made to improve its efficiency or versatility. During the period of this contract, a second optical channel was added, using light from the field of view which does not pass through the spectrometer entrance slit. This can be provided with an interference filter to monitor the intensity of any desired bright emission; however, it has frequently been the practice to rotate the interference filter in synchronism with the scan of the spectrometer so as to scan across the green line and give a record of its intensity

above the background. Sample tracings are given in CR-13, and
a detailed description is given in E.A. Lytle's thesis.

The sensitivity and versatility of this instrument are
greatly increased by the use of a delay-line memory unit which
is described in detail in CR-5. More recently, an automatic
readout which presents the data in punched paper tape has been
constructed by Maartense; the details are given in his thesis.
The memory has over 600 channels, each of 12 binary digits; it
can therefore store numbers up to 4,097. With this system, an
exposure of ten minutes or more to a faint source can be used,
and an excellent spectrum can be built up. Occasionally,
exposure times have been as long as an hour. The output tapes
are processed by a digital computer which prepares a second tape
to control a plotter. Until recently, this plotter has been
a flexowriter, and a sample spectrum produced in this way is
shown in Fig. 1. Recently, a second plotter using a Varian
recorder for its output has been constructed.

Now that the principle of the digital memory has been proved,
it would appear worthwhile to make use of commercial units
designed for multichannel pulse-height analysis. These are readily
adapted to the memory, or multiscaler, function, and have now
reached a price level which is competitive with the delay-line
unit. Undoubtedly, they will surpass it in reliability and
convenience of use. They will also permit the storage and sub-
traction of background spectra, extending the usefulness of the
spectrometer and memory combination still further, especially for
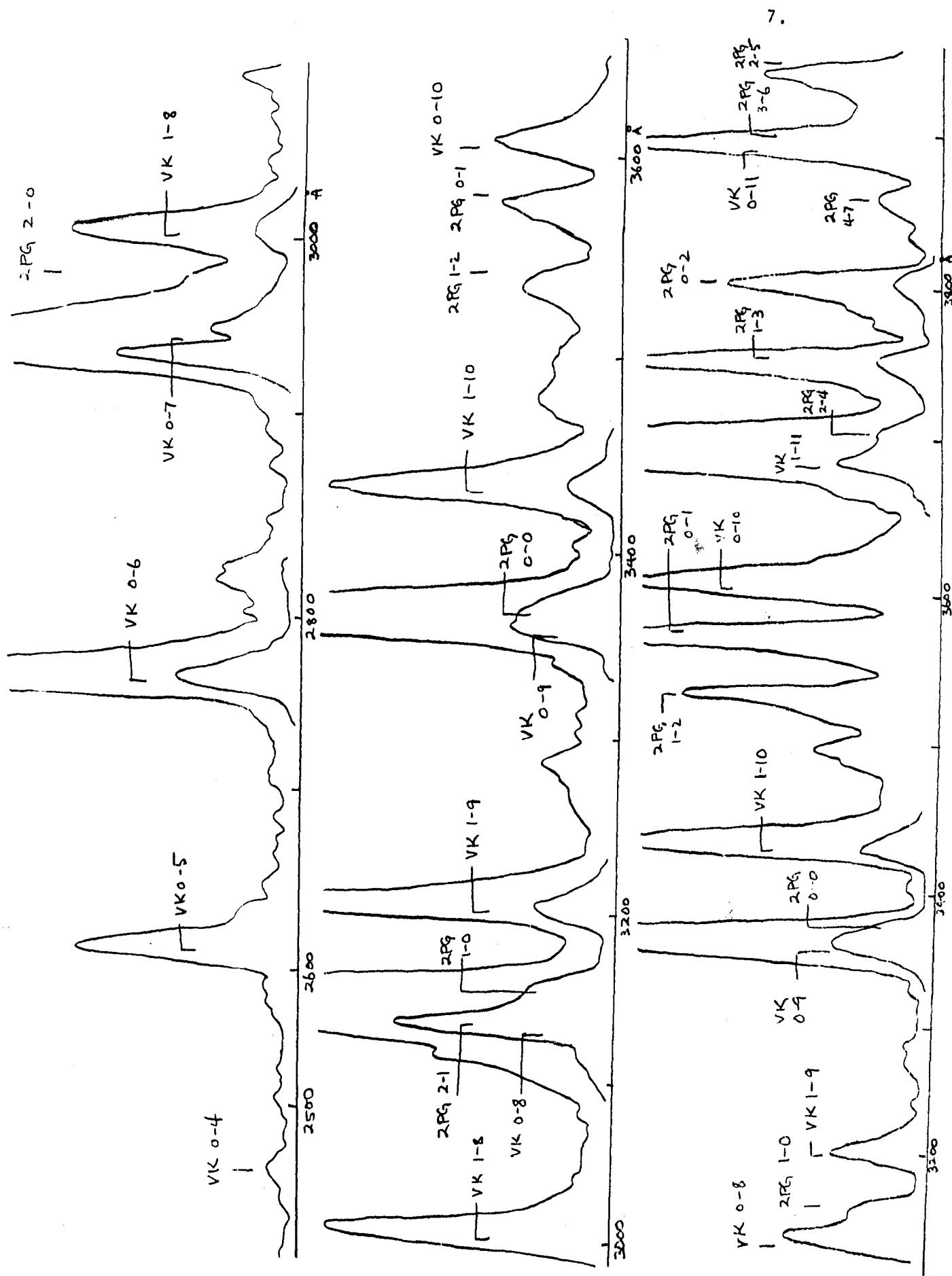twilight work.

Fig.1 Three Spectra of the Laboratory Source of VK Bands, Taken
With the Photoelectric Spectrometer and Memory Unit.

3.5 Twilight photometers

Birefringent Photometer

In this instrument, a birefringent filter of ammonium dihydrogen phosphate is used to discriminate against the white-light component of twilight. Although it was built about six years ago, it was considerably modified by Sullivan and a detailed description is given in his thesis. The modifications have greatly increased the reliability and stability of the instrument and it has given nearly three years' satisfactory operation with very little attention. Its principal use has been to observe the lithium emission in twilight, and several interesting effects have been discovered in this way. For a short time, it was used at the potassium wavelength instead, permitting the first observations of its presence and vertical distribution to be made.. So that both lithium and potassium can be studied simultaneously, a second similar photometer using a quartz birefringent element is now under construction. It is expected to be in operation during the summer of 1963.

Interference Wedge Photometer

This instrument is also designed for routine observation of the twilight, and is used for the sodium emission. Similar units are in service in Saskatoon and at Christchurch, New Zealand. The discrimination against white light is performed with the aid of a wedge interference filter having a bandwidth of about 15A, combined with a suitable chopper. The result is a 90-cycle signal corresponding to the sodium intensity and a dc signal corresponding to the white-light intensity. These can both be recorded, and if necessary combined to give a very reliable record of the sodium intensity. The instrument in Christchurch has given the first

detailed records of sodium intensity and vertical distribution
in the southern hemisphere, and a paper on these results is now
being prepared.

3.6 Michelson interferometer

This instrument is a conventional Michelson interferometer
with 3-in. square mirrors and a glass beam-splitter compensator.
It uses a cooled PbS detector and is designed to provide resolutions
between 500 and 1000 in the 1.0 to 2.0 μ region. Reference
fringes are provided by a cadmium lamp and photomultiplier detector
working through the same optical system. Interferograms may be
recorded either with a Visicorder or with a digital recording
system triggered from the cadmium fringes. The interferometer is
located in its own hut and is mounted on a concrete pier. This site
provides a clear view of the sky free from strong local lighting.
The instrument has produced interferograms of laboratory sources
but a problem of low sensitivity to the night airglow has been
encountered; there is, however, no reason to believe that this
problem is of a fundamental nature.

3.7 Low-Brightness sources

An important part of our work has always been the
absolute measurement of light intensity. This has been greatly
facilitated by the use of low-brightness sources which have been
referred by means of a spectrometer to a black body at a known
temperature. For use with a spectrometer, a source with a
continuous spectrum is convenient; these have been made using an
enlarging bulb operated at a constant temperature, a variable
aperture disc allowing a wide range of intensities to be selected,
and an opal-glass diffusing screen. Several of these have been

built and standardized in different wavelength ranges for different purposes, and others have been transported elsewhere to provide other workers with similar intensity calibrations.

This type of source is not satisfactory at wavelengths shorter than 4000 A; for the range down to 2500 A or less, a new source containing a high pressure hydrogen lamp and a ground quartz diffuser has been built and calibrated against a tungsten strip-filament lamp.

For the twilight sodium project in New Zealand, a source with a very narrow spectral bandwidth was required. For routine standardization, sources have been made with a mica interference filter of about 1A bandwidth; these have been calibrated against the normal low-brightness source using the scanning spectrometer. However, the one which was sent to New Zealand apparently changed its intensity by about a factor of 4, and an alternative had to be provided. In this one, the source was an Osram sodium arc lamp with its exciting current controlled by feedback from a vacuum photocell. This photocell received about half the light in the beam proceeding towards the ground glass. This source appears to have survived the journey to New Zealand and back without any mishap. Since then it has proved very useful in standardizing various sodium photometers and spectrometers.

3.8 N_2^+ temperature photometer

This instrument was designed for rapid measurement of rotational temperatures in aurora, and a detailed description was given in CR-19. It uses three narrow-band interference filters mounted on a rotating disc. One is used to measure the background light intensity away from the 3914A band of N_2^+; the

other two measure the band itself in two wavelength regions whose
intensity ratio is strongly dependent on the rotational temperature
of the band. The instrument is sensitive and precise, giving
measurements to better than $\pm 10^{\circ}$K over a wide range of temperatures.
However, the absolute accuracy is not as good as this because of
the difficulty of making a suitable calibration. With its response
time of about 1 second, it is able to measure temperature gradients
in aurora and to pick out interesting auroral forms for measurement.
Even without any measured auroral heights, it was possible to
construct an excellent temperature profile for the atmosphere
between 95 and 170 km. At present this instrument has been taken
out of service until the methods of measuring auroral height are
better developed.

3.9 Use of interference filters and interferometers with all-sky cameras

This is the subject of Scientific Report No. CR-3 by
Dr. D. Ramsden who spent the summer of 1960 working with the
project. He experimented with a number of arrangements for
photographing the sky in monochromatic light, or producing a
series of fringes across the field of view in order to enable an
emission to be distinguished from a background of twilight or
moonlight. The configurations tested all showed considerable
promise of usefulness, but in many cases were limited by poor
sensitivity making it necessary to use inconveniently long
exposures. It was suggested that the use of the ultra high speed
films which were becoming available at that time might make
enough difference to render the methods of considerable service.
However, due to other commitments none of the ideas have been
followed up so far.

3.10 Laboratory source of forbidden emissions

For laboratory work on the interpretation of auroral and airglow emissions, it would often be convenient to have a source of the forbidden lines or bands which are found in these spectra. A very successful tube which gives the Vegard-Kaplan bands free from serious contamination by other emissions has been developed and is described in Chandraiah's M.A. thesis. It consists of a 6-liter bulb with two side arms containing electrodes for a high-voltage discharge. It is filled at a pressure of a few centimeters with xenon which is then carefully purified by means of a barium getter. Then a very small amount of nitrogen is released by heating powdered sodium azide. When a discharge is run with a very low current, the Vegard-Kaplan bands are observable; the intensity is low, but the contamination by other emissions is small or negligible. It is likely that a similar source containing oxygen would emit the green and perhaps the red lines with a useful intensity.

3.11 Interference filters

As was noted in FRB a small program of production of interference filters has been maintained in order to provide filters of characteristics which cannot be obtained commercially. It is also useful to be able to coat interferometer plates as this is required. The narrow-band filters required for the temperature photometer were produced on this system, and their characteristics are described in CR-19. For the photometry of twilight lithium and potassium, narrow-band filters with about a 3-inch diameter were required, and these were also produced, as well as the wedge filters for the sodium twilight photometers. This equipment is operating very reliably, and is used from time to time when filters are required.

Chapter 4.   TWILIGHT AND DAYGLOW STUDIES

4.1 Twilight sodium

A detailed investigation of the seasonal variation of sodium twilight abundance and vertical distribution is reported in Scientific Report CR-4. The period covered is October 1958 to December 1959. Despite the very large annual variation of abundance, the shape of the vertical distribution hardly changes at all; the height may range over 3 to 5 km, but this height change can hardly be considered as the cause of the abundance variation.

Scientific Report CR-9 gives the details of a computer calculation of the atmospheric transmission functions for 4 wavelengths of interest in twilight studies. Moreover, the sodium calculations were done for 7 different distributions of ozone, representing as far as possible the extreme seasonal and geographical variation of this absorbing constituent. Graphs are given showing the derivatives of the transmission functions for the four wavelengths and the variation of the screening parameters for sodium as a function of the atmospheric ozone content. The screening heights and smearing widths are also tabulated.

Measurements of the sodium abundance at Christchurch, New Zealand, are reported in Scientific Report CR-11 and another paper still in preparation. In the first of these, the photographic method was used, giving results very similar to those found at Saskatoon, but displaced by six months. The second investigation, using an interference wedge photometer, gives considerably more detail, and also is giving vertical distributions. Since the latter material is not published yet, the seasonal variation found is reproduced in Fig. 2. The photoelectric results are somewhat higher than the photographic, and also higher than those found in
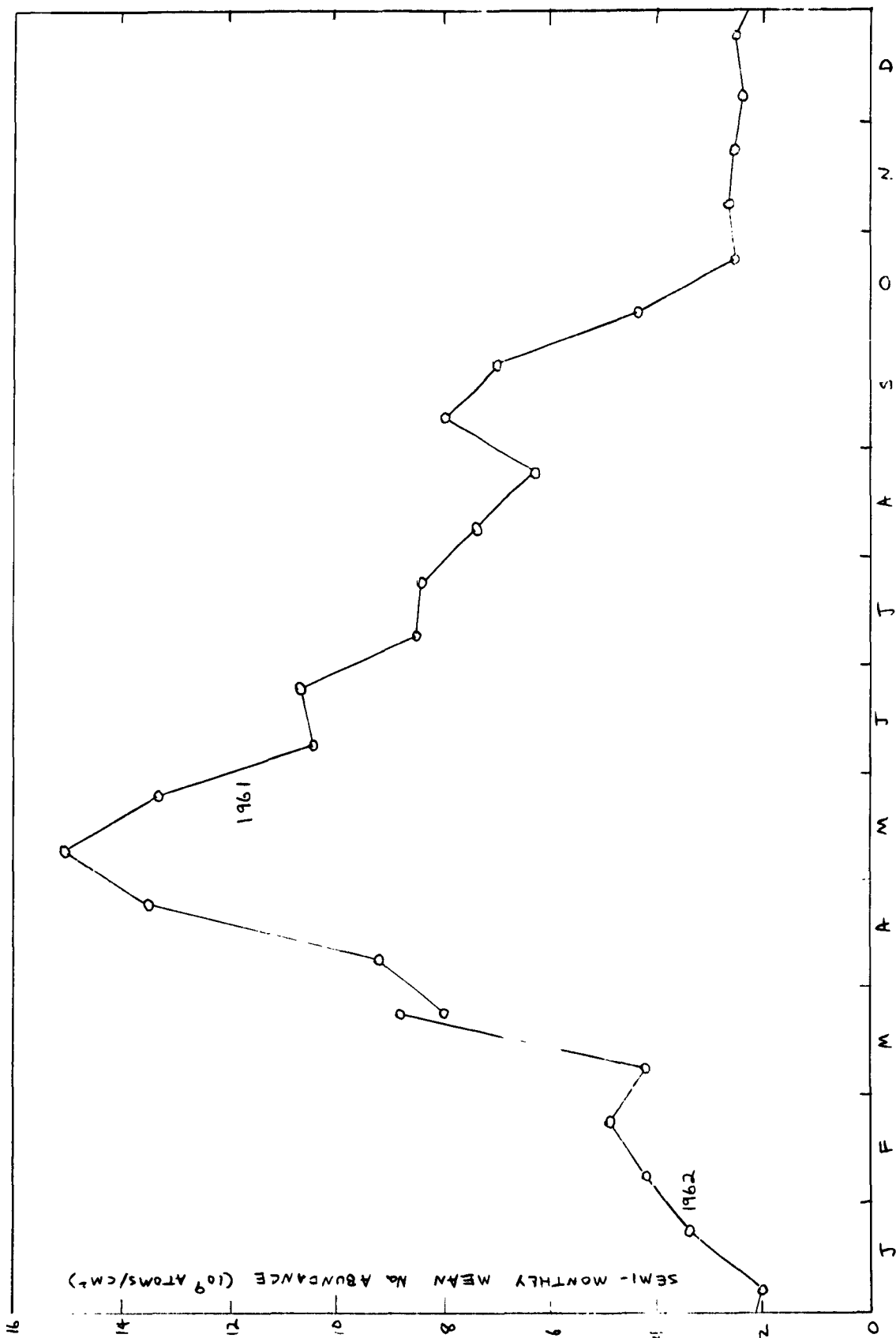
Fig. 2 Sodium Seasonal Variation at Christchurch, New Zealand

the northern hemisphere; it is quite possible that this is the result of a systematic error. However, there is no doubt of the basic conclusion that the abundance variation is a seasonal, not an annual, effect.

4.2 Other alkali metals in twilight

Measurements of twilight lithium since the middle of 1960 are given in Scientific Reports CR-12, CR-16, CR-18, and CR-20; further details are given in Sullivan's thesis. The abundance varies in a complicated and irregular manner, which does not seem to repeat from year to year. However, this has been difficult to study because of the large abundance peaks caused by certain thermonuclear explosions in the atmosphere. The most striking of these was observed in November 1962, when the brightness of the lithium lines was greater than that of the sodium for a short time. (A similar event occurred in 1958, before our program was begun.) Both these events seem to have been caused by intermediate-yield explosions at a height of 50 or 60 km. Another smaller but still significant increase occurred in October 1961, and is attributed to a 60-megaton explosion in the Soviet Union. Only a very small and short-lived peak was observed in July 1962 as a result of the explosion of July 9 at a height of 400 km. The peak of the lithium layer was found to be at an average height of about 79 km. Assuming that the lithium observed between the events just mentioned is of natural origin, the ratio of sodium to lithium could be derived. After correction for the different heights of the two layers, values between 5500 and 8000 were found for the ratio of sodium to lithium atoms.

It was also found possible to observe the potassium line at 7699A early in 1962. The abundance ratio sodium/potassium is almost exactly 50, and the vertical distributions are nearly identical. Since this ratio agrees closely with the value in sea-water, but not in any other source, this is evidence in favour of the hypothesis that upper atmospheric sodium is in equilibrium with the sodium in the oceans. However, the lithium abundance is far too high for this source, and it is proposed in Scientific Report No. CR-12 that the lithium comes primarily from meteorites, with the sodium and potassium primarily from the oceans.

A review of the topic "Metallic Emissions in the Twilight and Their Bearing on Atmospheric Dynamics" was prepared for the Symposium on Theoretical Interpretation of Upper Atmosphere Emissions in Paris, June 1962, and published as Scientific Report No. CR-16. It was concluded that dynamic effects must probably be invoked to explain the seasonal and geographical variations of sodium, but that the exact processes involved are still obscure. Far more promising as a technique for observing upper atmospheric circulations is the injection of substantial amounts of lithium from rockets; because of the small natural abundance of this element, a very large perturbation of the abundance can be produced in this way and it should be possible to trace it all over the world.

4.3 Infrared atmospheric oxygen bands

Work on the problem of the twilight infrared atmospheric oxygen band at 1.58μ was resumed in the summer of 1960 and has formed an important subject of investigation during the term of the present contract. The appearance of the 0-1 band in twilight was

found to have a strong seasonal intensity variation* being strong
in mid-winter and undetectable at mid-summer. It was also
possible*, by using infrared polaroid as a means of discriminating
against scattered white light, to make the observations over a
wider range of solar depression angles from about 1° to 8°. The
new observations were made at an azimuth angle of 90° from the
sun in order that the polaroid technique should be effective;
this direction of observation has the added advantage that the
comparatively wide field of view of the spectrometer leads to
little error.

These extended observations made it possible to carry out a
more detailed comparison between experiment and theory. It was
first found that the resonance phosphorescence mechanism for the
production of $O_2(^1\triangle_g)$ was inadequate*. Only by decreasing the
probability of collisional deactivation per gas-kinetic collision
to 10^{-12} was it possible to bring the calculated brightnesses
close to those observed. In this case, however, the calculated
decay of the twilight emission was very much slower than that
observed. Consequently, another mechanism of excitation was
sought. The most promising proposal was the reaction,

$$O_3 + h\nu = O_2(^1\triangle_g) + O(^1D).$$
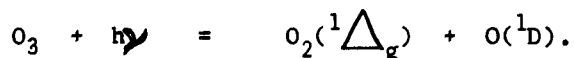
This dissociation process seems likely to occur as a result of
absorption in the Hartley continuum and calculations show that
it would be capable of exciting the twilight O_2 band with the

*see R.L. Gattinger, M.Sc. thesis (Chapter 8).

observed brightness. The observed rate of decay during the twilight can be matched with this mechanism provided that it is assumed that atomic oxygen is more effective in deactivating $O_2(^1\Delta_g)$ than molecular atmospheric particles. Even without this assumption the calculated decay is considerably faster than that attained with the resonance phosphorescence mechanism. The comparison between the observed and calculated decay curves is shown in Fig. 3.

The seasonal variation of the twilight O_2 band brightness is as yet unexplained. It is not yet clear whether this seasonal variation is due to a faster decay of the emission during twilight or whether it is due to a variation in the dayglow brightness.

A significant advance was made with the infrared spectrometer IR2 when Noxon succeeded in measuring both the twilight decay and the dayglow from 13 km. The aircraft observations were of the 0-0 band at 1.27 μ. The twilight decay of this band was similar to that observed from the ground with 0-1 band. The dayglow intensity was measured at 10 megarayleighs. This value is in agreement with the dayglow intensity calculated from the ozone dissociation mechanism. It may be noted however that experimental and theoretical evidence now suggests that the 0-0 band should be at least 60 times as strong as the 0-1 band. If this is the case, the ground observations from Saskatoon suggest that the maximum intensity observable in the 0-0 band might be as high as 60 megarayleighs.

It seems clear that the possibility of making aircraft observations of this band at many different latitudes and seasons should enable much fuller information to be obtained in the near future.
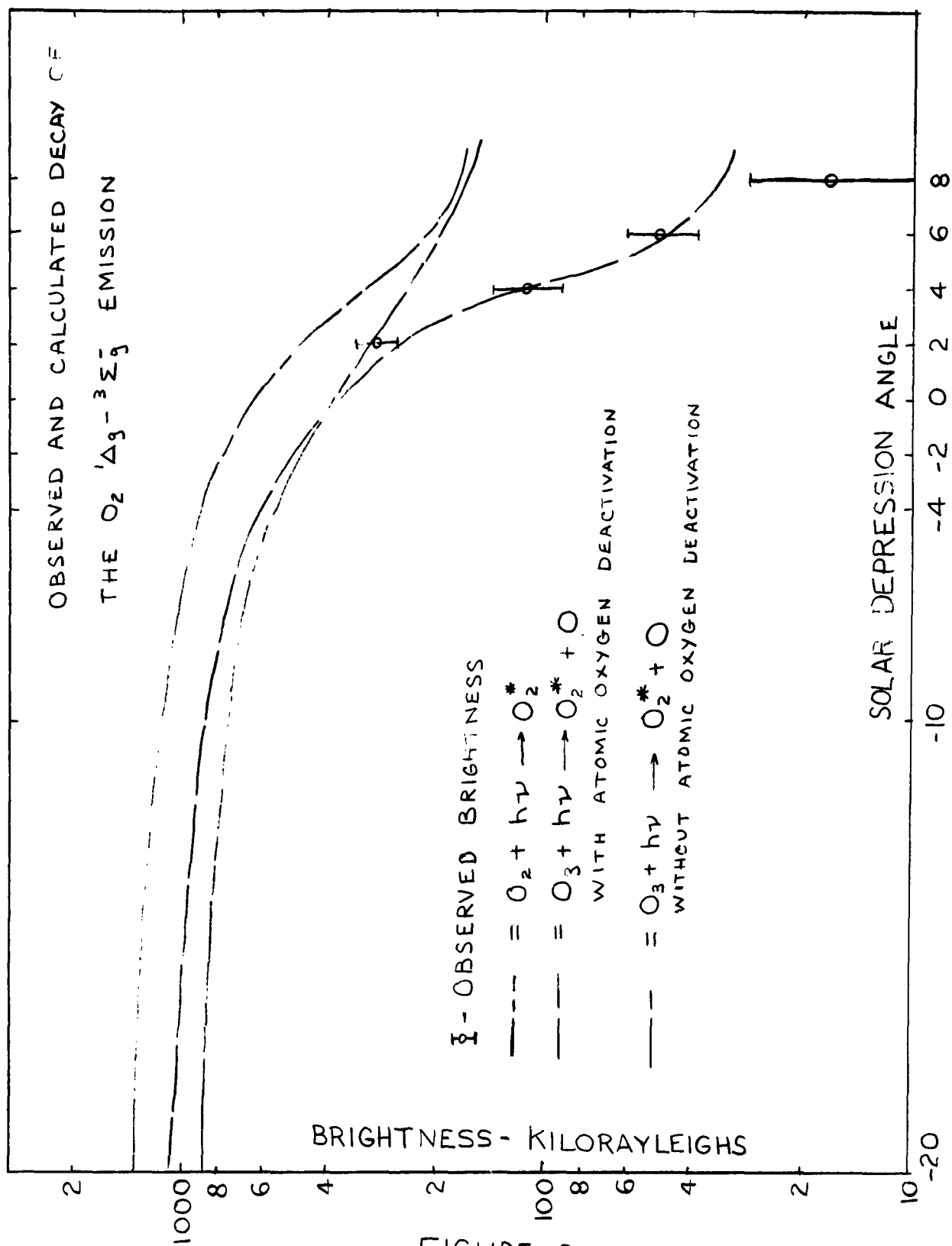
FIGURE 3

One important result of the theoretical calculations carried
out is the prediction that there should be considerable difference
in the dayglow height distributions to be expected in the cases of
the resonance phosphorescence and ozone dissociation mechanisms.
The calculated curves are shown in Fig. 4.

4.4 N_2^+ in the upper atmosphere

The study of the fluorescence of the N_2^+ first negative
bands in the twilight and in sunlit aurora has considerable
potential for advancing our understanding of the upper atmosphere
and the ionization processes there. This potential has largely gone
unrealized because of a lack of quantitative observations. The
first parts of a program which was undertaken to improve this
situation are reported in Lytle's Ph.D. thesis and in Scientific
Report No. CR-13. Twilight observations were made during aurora
and on undisturbed occasions as well; the green line was observed
simultaneously to give a measure of auroral activity in the field
of view. A follow-up investigation using similar techniques was
carried out by Maartense and is reported in his M.Sc. thesis;
these results have yet to be published. It appears that a twilight
enhancement of the N_2^+ band could be observed in 1960 but has since
disappeared. This led to an investigation of previous work on this
band, and it turned out that all successful series of observations
had been made within a couple of years of sunspot maximum. This
is also the case with the high sunlit auroral rays, which are due
to the emission of the same band system in fluorescence. There is
therefore some indication that the phenomenon of the N_2^+ twilight
is much stronger at times near sunspot maximum, but more
investigation is needed.

CALCULATED DAYGLOW PARTICLE CONCENTRATION OF O_2 $^1\Delta_g$ MOLECULES AT A SOLAR ELEVATION OF 20°

$O_3 + h\nu \rightarrow O_2^* + O$ WITH ATOMIC OXYGEN DEACTIVATION

$O_2 + h\nu \rightarrow O_2^*$ WITH COLLISIONAL DEACTIVATION

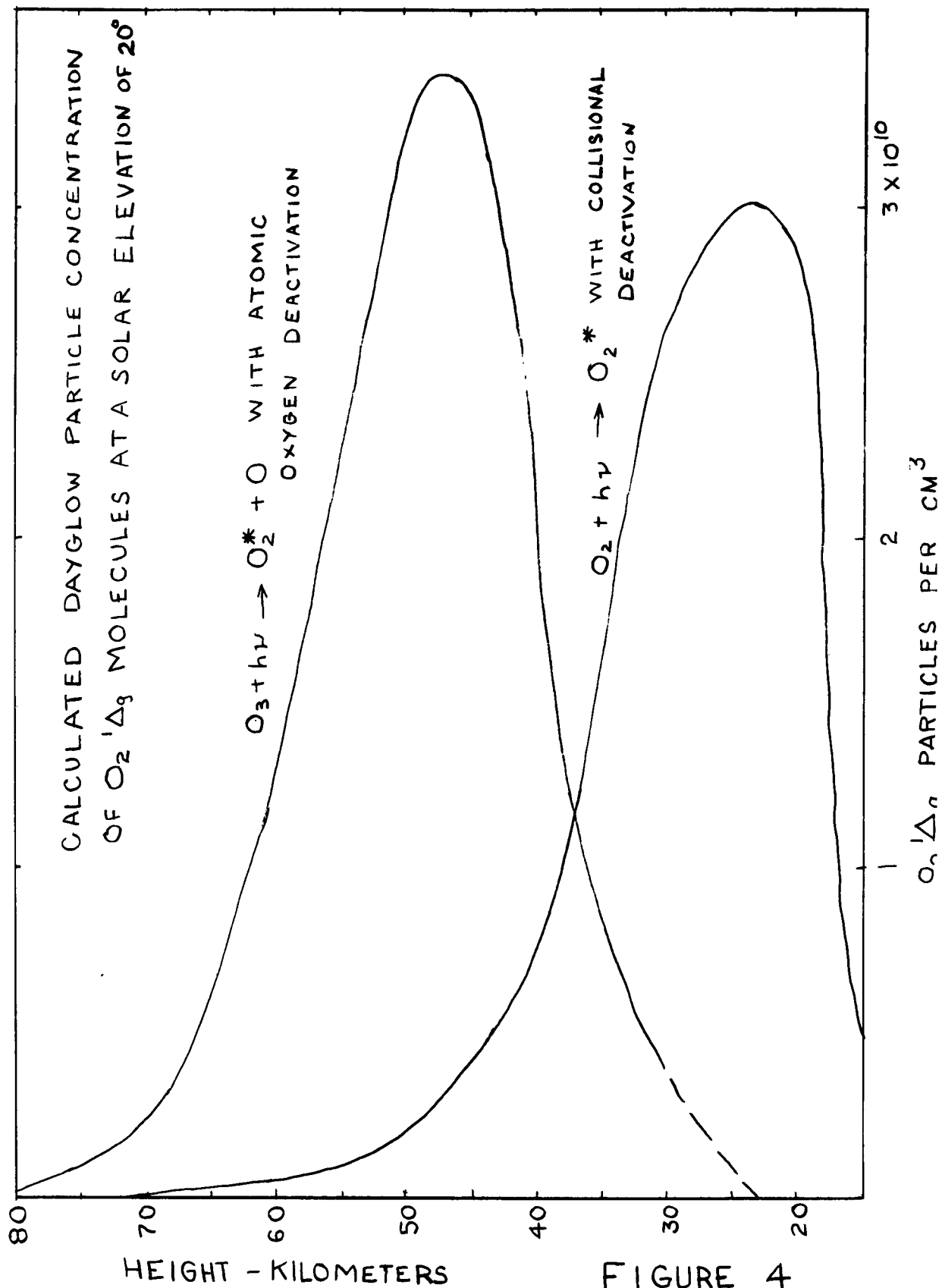HEIGHT - KILOMETERS

O_2 $^1\Delta_g$ PARTICLES PER CM^3

FIGURE 4

Several faint auroral displays were observed during these investigations, and they were found to exhibit fluorescence only above a height of about 130 km. It appears that some loss process for N_2^+ ions operates so rapidly below this height that a negligible steady-state concentration of them can be built up. This process can hardly be dissociative recombination, and there is a strong suggestion that either charge-exchange or ion-atom interchange are the processes responsible. If this is the case, the twilight in absence of aurora must be produced at a much greater height in the 550-km region. This suggests that it is produced by ionization by solar extreme ultraviolet radiation, and perhaps it is this radiation which is strongest near sunspot maximum. Possibly another contributing factor is an increase in N_2 density at great heights.

This and previous work was reviewed at the Paris Symposium on Theoretical Interpretation of Upper Atmosphere Emissions under the title "The Production of N_2^+ in the Atmosphere"; it has been published as Scientific Report No. CR-14. Although the observations of N_2^+ emission in aurora and during polar-cap absorption events were noted, it was pointed out that twilight measurements are far more valuable since they can give the concentration of N_2^+ ions and not merely the production rate. During bright sunlit aurora, this concentration can reach values as high as 10^5 ions/cm^3, and it is possible that even higher values occur at times. Faint aurora at more usual altitudes seldom produces an ion concentration greater than 10^3 ions/cm^3, and the maximum density tends to be in the 150 to 200 km region.

The intensity of the 3914A band in the nightglow was
measured on several occasions and found to be in the range
20 - 50 R. This argues against the idea that the green line
in the nightglow is produced by particle bombardment.

4.5 Rocket-borne sodium photometer for dayglow observations

There is some experimental evidence* that the sodium
content of the upper atmosphere in daytime is larger by a factor
of 3 or 4 than in twilight. This result is very difficult to
understand theoretically, and further evidence on the matter is
urgently required. Moreover, if the intensity is large during
the daytime, a good measurement of its vertical distribution
would be very important in pointing towards an explanation. The
photometer to be described has been designed to be flown through
the sodium dayglow layer by means of a suitable rocket. It uses
a special optical chopper of our own manufacture, incorporating
6 wedge-shaped interference filters each occupying 60° of the
circumference. Three of the filters are narrow-band ones, and
three have considerably broader bands but lower peak transmission.
All of them are centered on the wavelength of the D lines. The
transmission of the wide-band filters is adjusted so that the
solar continuum is not chopped as the disc rotates. However, the
transmission of the wide-band filters for the sodium lines is
considerably less than that of the narrow-band ones, and therefore
the sodium lines are chopped. The resulting 90-cycle signal is
amplified, detected, and telemetered to ground, along with the dc

*J.E. Blamont and T.M. Donahue, J. Geophys. Res., 66, 1407 (1961).

signal which is a measure of the white-light background.
Transistor electronics have been designed and built, and the
whole instrument, including the motor, operates off three
mercury batteries. After having been tested on the twilight,
the instrument will be flown in an aircraft at the solar
eclipse of July 20, 1963. After this, it is hoped to fly
the instrument in a rocket at White Sands in cooperation with
the Kitt Peak National Observatory.

Chapter 5.   AURORAL SPECTRA AND RELATED TOPICS

5.1 Vibrational intensity ratios of first negative N_2^+ bands

A striking feature of many patrol spectrograms has been the variations in the intensity ratio of the 1-3 and 0-2 first negative N_2^+ bands. A survey of plates obtained with the 2-in. high-speed patrol spectrograph in early 1960 showed a correlation* between increasing values of this intensity ratio and intensities of the hydrogen lines. Spectra of low-latitude and sunlit aurora also show abnormal values of this ratio which are undoubtedly connected with high atmospheric temperatures exceeding 1000° K. A high dispersion study was therefore carried out to establish whether the abnormal ratios of the $\triangle v = 2$ band sequence ratio were useable generally as a measure of upper atmospheric temperatures. This was done* by comparing the rotational temperatures of the λ 4278 N_2^+ band with the $\triangle v = 2$ vibrational ratio. It was found, however, that below 1000° K no reliable correlation existed. Higher dispersion spectra* obtained with the 9-in. spectrograph showed that the O II multiplet 1 which underlies the 1-3 band is sufficiently strong to account for the intensifications of this band observed with low resolution instruments. Consequently, it appears likely that the correlation between the hydrogen emission and the high band ratios observed with the patrol spectrographs reflects a correlation between the intensities of the lines of ionized oxygen and those of hydrogen rather than either

*M. Ahmed, M.A. thesis (see Chapter 8).

the production of abnormally high temperatures or even of abnormal

vibrational band ratios.

5.2 Vegard-Kaplan bands in aurora and laboratory

The VK bands in the aurora have been carefully measured

with the photoelectric spectrometer and delay-line memory unit. To

aid in the interpretation of the results, a parallel laboratory

investigation of the same bands was carried out. The system of

intensity standards had to be extended to about 2500 A to make

this possible. The results have not yet been published, but they

are reported in the Ph.D. thesis of L. Broadfoot and the M.Sc.

thesis of G. Chandraiah.

The laboratory investigation showed that the variation of the

electronic transition moment from band to band has a very important

effect on the relative intensities within the system; the square

of this moment, which controls the intensity, varies over a range

of the order of 30 to 1. While the effect on the bands observable

at the ground from the upper atmosphere is not very large, the

calculation from these intensities of the total system intensity

is greatly affected. This is because the bands in the 2000 A

region are much fainter than would have been expected for a

constant transition moment. The faintness of these bands had in

fact already been observed in the rocket spectra of Fastie and

Markham, and their somewhat puzzling result is now satisfactorily

explained.

The auroral measurements were undertaken in the attempt to

understand the excitation process of the metastable level which

gives rise to the VK bands. It was found that very little of

this excitation can be due to direct transitions from the ground

state to the metastable state during electron impact; most of the
excited states must arise by cascading from higher levels through
the emission of the first and second positive band systems. It
appears that the height at which the VK bands are emitted must be
fairly large, since the rotational temperature is consistently
about 800°K. These results will be published as soon as possible.

5.3 Infrared auroral spectra

The recording of infrared spectra of the aurora beyond
1.0 μ remains a major objective of our program. Further results
were obtained with the spectrometer IR1 in 1960 but since then a
lack of bright aurora has hampered observations. One of the major
purposes of the Michelson interferometer was the recording of
spectra of aurora from lower intensity but more stable displays.
This purpose has not yet been achieved. Likewise an important
function of the aircraft-borne spectrometer, IR2, is the recording
of auroral spectra initially in the 1.0 to 2.0 μ region. It was
hoped that the ability of the aircraft-borne spectrometer to
operate in regions of high auroral probability and to obtain
observations relatively free from atmospheric absorption would
make it possible to obtain much improved auroral spectra. However,
the use of this instrument for this purpose is hampered through
the limitation of the field of view of the instrument through the
side-window of the aircraft; it is hoped that it can be installed
in a transparent dome which would make zenith observations possible
and provide a greater flexibility in the direction of observation.

5.4 Patrol spectrograph observations of aurora

The results obtained with the 2-in. high-speed patrol

spectrograph are fully described in CR-15 (see section 8). This report confirms the preliminary suggestion in FRB that at Saskatoon hydrogen-rich arcs or bands of low brightness are observed to the south of the main auroral activity in the evening hours and that this zone of proton precipitation becomes coincident with the main bright auroral display towards midnight (possibly even fading away or retreating to the north). After midnight stronger hydrogen lines may again be observed frequently to the north of the main luminosity. Similar results have, of course, been obtained in Alaska, Norway and the U.S.S.R.

On the basis of this work we are attempting to set up a line of stations with similar spectrographs at Saskatoon, Flin Flon and Churchill. These stations lie on a straight line and the fields covered by the patrol spectrographs should overlap at an elevation angle of 15° for the Churchill - Flin Flon pair, and 22° for the Flin Flon - Saskatoon pair. It is hoped to synchronize exposures between the three stations and obtain a complete record of the occurrence of hydrogen emissions along this line in relation to other auroral forms. This program should operate during the IQSY.

5.5 Five-channel photometry

A 5-channel photometer was constructed primarily to be used as a rocket-borne instrument. Five separate channels with individual photomultipliers and interference filters were provided. The development and construction of this photometer was not a charge upon the Contract. However, when it became necessary, due to the fire at the Fort Churchill rocket range,

to postpone the rocket experiment, the photometer was adapted
to ground observations of aurora. The high speed of response of
this instrument proved suitable for measurements of time-delays
between the auroral green line and the first negative N_2^+ bands
and other auroral emissions. It was found that in type-B red
aurora the apparent lifetime of the $O(^1S)$ state decreased to
about $0.48 \pm .06$ seconds compared to $0.67 \pm .06$ seconds in
normal aurora. This may indicate that collisional deactivation
of the $O(^1S)$ state occurs in type-B red aurora and is one factor
contributing to the reddening.

Relative brightness measurements showed for type-B red
aurora compared to normal aurora an appreciable intensification
of up to 50% for the 1PG emission compared to the 1NG N_2^+ bands.
At the same time there was observed a decrease of about 30% in
the intensity of the green line compared to the 1NG bands.

Measurements were also made of the height distributions
of the green line, the red lines, the N_2^+ bands, the 1PG N_2 bands
and the H_α line. A report on these observations will be
prepared in the near future. A further description of the
results is given in the abstract of Mr. W.F.J. Evans' thesis
in Chapter 8.

Chapter 6.   NIGHT AIRGLOW SPECTRA

6.1   Infrared airglow investigations

A considerable effort was put into the balloon spectrometer program designed to obtain and measure the brightness of the $\triangle$v = 1 OH bands. These are inaccessible from the ground because of lower-atmospheric thermal emission and absorption. A successful flight was made in April 1960 although results were obtained only up to 9 km. Apparently the height attained was not quite great enough, or more likely a small amount of unbalanced thermal radiation from the mirror chopper masked the emission of the 1-0 OH band. It was possible to put an upper limit of 700 kR on the zenith brightness of this band.

At this point it became clear that the Canadian Armament Research and Development Establishment which carried out the balloon flights for us had developed a larger balloon borne spectrometer more suited to the further investigation of this problem. Consequently, we have not attempted to follow up this investigation further ourselves. The CARDE spectrometer has been flown successfully and has been able to obtain the spectrum of the $\triangle$v = 1 sequence.

A report on the night airglow results mentioned briefly in FRB was prepared (CR-8). The significant results of this study are set out in the abstract in Chapter 8.

Chapter 7.   UPPER-ATMOSPHERIC TEMPERATURES

A review of the topic "Temperatures Deduced From Aurora and Airglow Spectra" was prepared for the Copenhagen Symposium on Aeronomy, July 1960, and published as Scientific Report CR-1. Although a considerable number of types of measurement exist, by far the most useful was found to be the rotational temperatures from N_2^+ negative bands in aurora; next in importance come the Doppler bandwidth measurements with interferometers. With modern spectroscopic techniques, the limiting factor in the construction of an atmospheric temperature profile is not the measurement of the temperature, but rather the determination of the corresponding height. In principle this is readily done by 2-station photography of aurora, but in practice this procedure offers many difficulties and further developments would appear to be warranted. It was found possible to construct, from spectroscopic data alone, a temperature profile of the atmosphere from about 70 to 250 km, with a tentative extension to 500 km. The minimum temperature was 180°K at 90 km and the gradient above 110 km was 5.2°/km.

A more recent investigation using the 5-inch spectrograph is described in Scientific Report No. CR-10. By using wide slits, it was found possible to reduce the exposure times to as little as 5 minutes with no sacrifice of accuracy. When the sky near the horizon was projected on the slit, it was often possible to observe the temperature gradient along the vertical extension of an auroral form; gradients of about 6°K/km were found at times. Studies of type-A red and sunlit auroral forms yielded many temperatures in the 700-1000°K range.

Another recent investigation with the photoelectric temperature

photometer is described in Scientific Report CR-19. Although

no height measurements were available from this investigation,

it was still possible to construct an atmospheric temperature

profile extending from 160^OK at 95 km to 580^OK at 170 km. The

temperature gradient throughout this whole region was 6.0^O/km,

slightly greater than was found in the review mentioned above.

The lowest temperature observed was 140 ± 20°, lasting for a

period of 10 minutes. It was found, as in Report CR-10, that

most auroral forms, when observed well away from the zenith,

have an easily observable temperature gradient along their

vertical extension; indeed, use was made of this result in

constructing the temperature profile just mentioned.

Chapter 8. ABSTRACTS OF SCIENTIFIC REPORTS AND THESES

8.1 <u>Scientific reports</u>

CR-1   D.M. Hunten. Temperatures Deduced From Aurora and Airglow
        Spectra. Ann. Géophys., <u>17</u>, 249 (1961).

        A temperature profile for the upper atmosphere between
        70 and 250 km, extended tentatively to 500 km, is constructed
        from spectroscopic temperatures. The most important are ro-
        tational temperatures from N_2^+ negative bands in aurora, both
        normal and sunlit, and measurements of Doppler widths of the
        forbidden lines in the night and twilight airglow. The profile
        has a minimum of $180^\circ K$ at 90 km and a linear gradient of
        5.2°/km above 110 km to perhaps as far as 400 km. Suggestions
        for further work are included.

CR-2   J. Noxon and A. Vallance Jones. An Auroral Emission in the
        2.0-2.2μ Region. J. Atmosph. Terr. Phys., <u>18</u>, 342 (1960).

        This note reports an attempt to observe auroral emission
        in the 2.0-2.5 micron region using an infrared grating spectro-
        meter. Observations were made during bright active aurora with
        a spectral slitwidth of 300 A. No emission was observed from
        ordinary active aurora with visual brightness up to inter-
        national brightness coefficient III. On one occasion with
        bright active type-B red aurora a feature of total intensity
        60 kR was observed at about 2.14 μ. This emission is tenta-
        tively identified as the 0-2 Meinel band of N_2^+.

CR-3   D. Ramsden. Experiments With Monochromatic All-Sky Cameras.
        University of Saskatchewan Scientific Report No. CR-3. 1960.

        Several optical systems for observing monochromatic
        emissions with an all-sky camera are described and discussed.
        They were tested at wavelengths of 6300, 5577, and 3914 A
        and should also be useful at 5893 A. They appear capable of
        gathering useful data but with ordinary fast films require
        exposures of half an hour or more. New films with tenfold
        greater speed may reduce this limitation. A preliminary in-
        vestigation of twilight fluorescence in the 3914 A band of N_2^+
        suggests that it is only present during auroral activity.

CR-4   R. Bullock and D.M. Hunten. Vertical Distribution of Sodium
        in the Upper Atmosphere. Can. J. Phys., <u>39</u>, 976 (1961).

        The sodium twilight has been observed over the period
        October 1958 to December 1959 with a birefringent photometer.
        Abundances and vertical distributions have been found for 120
        twilights. The abundance variation is similar to that found
        previously but is more nearly symmetrical about the solstices.
        A small seasonal variation in peak height is found, 3 to 5
        kilometers with maximum in March. In general, changes in
        abundance cannot be correlated with changes in distribution;

however, a few exceptions to this were found in June and
July, when a large overnight increase in abundance accom-
panied a large decrease in the height of the whole distribution.

CR-5   L. Broadfoot and D.M. Hunten. A 600-Channel Memory Unit for
Improving Signal-to-Noise Ratios. University of Saskatchewan
Scientific Report, (1961).

An "ultrasonic delay-line memory unit" was constructed
to add and store successive spectra obtained from a rapid-
scanning auroral spectrometer. Information from a photoelectric
detector is presented to the memory where it is summed and
stored as a serial binary number. The memory is divided into
more than 600 ten-digit channels with a capacity of $2^{10}-1$
counts per channel. The internal program provides sequential
access to channels. An input unit provides continuous summation
and temporary storage of random information pulses since the
permanent memory can only be entered once every 2.22 milli-
seconds. A description of the operation of the memory and the
functional arrangement of the electronic circuit is given.

CR-6   J. Noxon and A. Vallance Jones. A Balloon-Borne Spectrometer
for Study of the Airglow Beyond 2.0 μ. Can. J. Phys., 39,
1120 (1961).

An account is given of the design, construction, and
flight of a balloon-borne infrared spectrometer intended for
the study of the night airglow spectrum in the 2.2- to 3.5-μ
region. This region is not accessible from the ground because
of the strong thermal emission from the lower atmosphere. The
spectrometer employed a 64 x 64 mm plane diffraction grating
and a liquid-oxygen-cooled PbS detector. The spectral slit
width was 700 Å and the noise-equivalent differential bright-
ness was about 2×10^{-8} watt. cm^{-2}, $sterad^{-1}$. $micron^{-1}$. The
observations permitted an upper limit of about 700 kR (kilo-
rayleighs) to be placed on the zenith brightness of the 1-0
OH band; this value is very close to that predicted by Chamberlain
and Smith. No emission was observed between 2.3 and 2.7μ.
This establishes an upper limit on the zenith brightness of
emission features in this region at 200 kR, for features narrow
compared to the spectral slit width, and at about 3000 kR/micron
for the differential brightness of any continuous emission.
The general design of spectrometers for this wavelength region
is considered and a discussion is given of improvements suggested
by the results of this experiment.

CR-7   J.F. Noxon. Observation of the $(b^1\Sigma_g^+ - a^1\Delta_g)$ Transition in
O_2. Can. J. Phys., 39, 110 (1961).

The Q branch of the (0,0) band of the electric quadrupole
$(b^1\Sigma_g^+ - a^1\Delta_g)$ transition in O_2 has been observed at 1.908μ in
the emission spectrum of a discharge through O_2 and He. By a
comparison with the (0,0) atmospheric O_2 band $(b^1\Sigma_g^+ - X^3\Sigma_g^-)$,
the absolute transition probability for the (b-a) system has
been found to be 2.5×10^{-3} sec^{-1}, with an uncertainty of a

factor of 2. The (0,0) band of the infrared atmospheric $(a^1\Delta_g - X^3\Sigma_g^-)$ system of O_2 has also been observed in emission. Using the observed intensity of the (0,1) atmospheric O_2 band in the aurora and airglow one may predict that the (0,0) (b-a) band should be detectable in a strong aurora if observations are made from high altitude.

CR-8   D.E. Shemansky and A. Vallance Jones. New Measurements of the Night Airglow Spectrum in the 1.5 μ Region. J. Atmosph. Terr. Phys., 22, 166 (1961).

Measurements of the spectra of the night airglow emission in the 1.40 – 1.65 μ region have been made at a spectral slit width of 25 Å, with a grating spectrometer using a germanium photoconductive detector. The rotational fine structure of the 3,1 and 4,2 OH bands was partially resolved and the 2,0 OH band was observed for the first time. Rotational temperatures between 200 and 225°K were obtained from the P-branch of the 3,1 band. A mean value of 66 kR was obtained for the absolute zenith brightness of the 4,2 OH band. A van Rhijn measurement of the height of the OH emitting layer gave a value of 69 km.

CR-9   D.M. Hunten. Transmission Functions for Twilight Studies. J. Atmosph. Terr. Phys., 24, 333 (1962).

Transmission functions have been calculated by electronic computer for the radiations of Na, Li, K, CaII, and N_2^+; for Na, several different ozone distributions were used. Screening heights and "smearing widths" have been found for each function. For Na, their variation with ozone abundance has been plotted, and interpolation formulae given to allow their estimation. With the better ozone distributions assumed here, the deduced heights of the sodium layer are about 3.5 km higher, when compared with previous work.

CR-10   A.E. Johanson and A. Vallance Jones. Variations With Height and Form of N_2^+ Rotational Temperatures in Aurora. Can. J. Phys., 40, 24 (1962).

The height variations of N_2^+ rotational temperatures in aurora have been measured from the long slit spectra of suitable auroral forms near the northern horizon. The results show a definite increase in temperature with emission height. Under the best observing conditions, temperature gradients of about 6°K/km were found in the 100- to 160-km region. Temperatures were also obtained from different forms and types of aurora using a narrow field of view. The results indicate that type-A red and sunlit auroral forms give higher temperatures more frequently than do more normal types; the former show many temperatures between 700 and 1000°K which correspond to heights in the 200- to 250-km range. When the temperatures obtained were classified according to the form of aurora, it was found

that diffuse and pulsating surfaces also show higher tempera-
tures more frequently than do bands and arcs. The temperatures
obtained from these forms quite often correspond to heights
in the 150- to 190-km range.

CR-11   B.A. Tinsley and A. Vallance Jones. The Seasonal Variation
of the Twilight Sodium Airglow in the Southern Hemisphere.
J. Atmosph. Terr. Phys., 24, 345 (1962).

The plateau brightness of the sodium twilight airglow
has been measured near Christchurch, New Zealand, by photo-
graphic spectroscopy between July 1960 and September 1961. A
seasonal variation with a maximum in mid-winter and a minimum
in mid-summer was observed. This is similar to the seasonal
variation in the northern hemisphere.

CR-12   H.M. Sullivan and D.M. Hunten. Relative Abundances of Li, Na,
and K in the Upper Atmosphere. Nature, 195, 589 (1962).

Potassium was observed in twilight with a peak density
of 2.4 atoms/cm^3 at 96 km. The ratio Na/K was very close to
50, agreeing with the ratio in sea-water but not in any other
likely sources. Na/Li was about 5500. The most reasonable
explanation is that Na and K come mostly from the oceans and
Li mostly from meteors. The seasonal variation of Li is dis-
cussed; there appear to be maxima in November and January.

CR-13   E.A. Lytle and D.M. Hunten. Observations of N_2^+ Twilight and
Sunlit Aurora. Can. J. Phys., 40, 1370 (1962).

The 3914-Å band of N_2^+ has been observed in the zenith
at twilight by a photoelectric spectrometer; simultaneous
measurements of the 5577-Å line were made as a check on auroral
activity. A small twilight enhancement was probably observed
in the absence of aurora in 1960, but it could not be detected
in 1961. After subtraction of this background, the auroral
measurements showed N_2^+ densities of about 1000 ions/cm^3 at
160 km, with a sharp decrease at lower altitudes; some displays,
presumably located near 100 km, showed no twilight effect at
all. It is suggested that N_2^+ ions are rapidly removed in the
100-km region by either charge-exchange or ion-atom inter-
change reactions which convert them into NO^+ or some other
ion. The ions in the twilight airglow are therefore probably
located at 550 to 620 km, being produced there by solar extreme
ultraviolet. However, this process requires a much higher
N_2 concentration at such heights than is normally supposed.
This may be produced at times of high solar activity, and es-
pecially during magnetic storms.

CR-14   D.M. Hunten. The Production of N_2^+ in the Atmosphere. Planet.
Space Sci., 10, 37 (1963).

Studies of the emission of the first negative bands of N_2^+ in aurora (normal and sunlit) and twilight are reviewed. Ion densities of 10^3 to over 10^5 ions/cm^3 are deduced for sunlit aurora. A very rapid loss process appears to limit the ion density below 150 km, and reactions of charge-transfer or ion-atom interchange are suggested. The normal twilight must therefore occur in the F region, the ions being produced by solar extreme ultraviolet e.u.v. It is suggested that this effect may be observable only near sunspot maximum, when the e.u.v. flux is largest and perhaps the N_2 concentration in the F region is unusually large. Quantitative difficulties in accounting for the intensity of the twilight and of high sunlit aurora seem to require this enhanced N_2 concentration when solar activity is high, and especially during large magnetic disturbances. Support from satellite-drag and ionospheric observations is found for this idea.

CR-15   L.E. Montbriand and A. Vallance Jones. Studies of Auroral Hydrogen Emissions in West-Central Canada. I. Time and Geographical Variations. Can. J. Phys., 40, 1401 (1962).

An account is given of some relations, between the appearance of the hydrogen lines and the other features of auroral spectra found, from the study of I.G.Y. patrol spectra and from high time resolution spectra obtained during the winter of 1959-1960. At Saskatoon it was found that quiet, weak auroral arcs characterized by strong hydrogen emissions occur in the evening at the southern fringe of auroral activity while brighter forms with weak hydrogen emissions occurred simultaneously to the north. The north-south-north progression of the hydrogen emissions found by Rees, Belon, and Romick in Alaska was observed from Saskatoon. The observations show that there is a wide zone of hydrogen emission which is always present and which becomes brighter and is displaced to the south during periods of magnetic disturbance. Quiet arcs showing relatively strong hydrogen emission are characteristic, in the evening, of the southern edge of this zone.

CR-16   A. Vallance Jones. Metallic Emissions in the Twilight and Their Bearing on Atmospheric Dynamics. Planet. Space Sci., 10, 117 (1963).

The possibilities are reviewed of obtaining information about dynamic processes in the upper atmosphere by observing variations in the concentrations of naturally occurring and artificially introduced metallic atoms detected by their twilight fluorescence. It is concluded that while in the case of natural sodium, dynamic effects are probably responsible for the seasonal variation, the exact processes involved remain obscure. Even less is known in the cases of natural lithium, potassium and calcium. Theories of the origin and seasonal variation of upper atmospheric sodium are reviewed. The observation of the twilight fluorescence of lithium, after

the injection of quantities of the metal into the mesosphere and lower thermosphere, seems to be a promising technique for the study of upper atmospheric dynamics.

CR-17   J.F. Noxon and A. Vallance Jones. Observation of the (0,0) Band of the ($^1\Delta_g - ^3\Sigma_g^-$) System of O_2 in the Day and Twilight Airglow. Nature, 195, 157 (1962).

An observation of the 0-0 infrared atmospheric band of O_2 at 1.27 μ using an aircraft-borne infrared spectrometer is reported. This band was observed in emission in the dayglow with an intensity estimated at 10 megarayleighs reduced to zenith and corrected for atmospheric absorption. The band was also observed in the twilight to decay in a similar manner to the 0-1 band of the system observed from the ground.

CR-18   H.M. Sullivan and D.M. Hunten. Lithium Twilight at Saskatoon, 1960-61. Nature, 193, 1064 (1962).

Lithium with abundance 10^6 atoms/cm^2 was observed during August, September, and October 1961. At the beginning of November, it suddenly increased to 2.5 x 10^7 atoms/cm^2, then falling and fluctuating about a value half as great for the next two months. The large peak is tentatively associated with one or both of the large thermonuclear explosions set off by the U.S.S.R. a few days earlier. However, there is some evidence for a natural peak of abundance at the same season. The vertical distribution showed a maximum at 81 km, about 7.5 km lower than sodium. The sodium/lithium ratio in the upper atmosphere is estimated as 8000 for October.

CR-19   D.M. Hunten, E.G. Rawson and J.K. Walker. Rapid Measurement of N_2^+ Rotational Temperatures in Aurora. Can. J. Phys., 41, 258 (1963).

A description is given of a photoelectric "temperature photometer" which gives a temperature reading from aurora in about one second. It uses two narrow-band interference filters to measure the intensity in two parts of the bright N_2^+ band at 3914 Å, and a third to allow a background measurement. The reading is presented on a meter and is independent of the auroral intensity over a wide range. Observations of aurora have permitted construction of a temperature profile for the atmosphere from 95 to 170 km, showing a gradient of 6.0°K/km. A lowest temperature of 140-20°K was observed for a period of several minutes. Diffuse surfaces appear from their temperatures to occur anywhere from 100 to 160 km.

CR-20   W.A. Gault and D.M. Hunten. High Abundance of Twilight Lithium, November 1962. Nature (to be published).

A large enhancement of lithium abundance as observed in twilight occurred during November 1962; the intensity rose to

a value greater than that of the sodium lines at the same time
of year. The source is believed to be an intermediate-yield
thermonuclear explosion at a height of 48 to 64 km on October
26. The intensity was first observed to rise about four days
after the explosion, and the peak was about seventeen days
after; the half life of the decay is about a week. This trend
is strikingly similar to that observed after a similar explosion
in 1958. It is concluded that both events were indeed produced
by debris from a thermonuclear bomb.

Theses Written on Work Done Under the Contract

E. A. Lytle, Resonance Scattering by N_2^+ Ions in the Upper Atmosphere,
Ph.D., September 1961. See Report CR-13.

I. Maartense, An Observational Study of the N_2^+ Twilight Enhancement,
M.Sc., September 1962.

An observational study has been made of the 3914 Å band
of N_2^+ in the twilight airglow. Improvement of the signal-to-
noise ratio of the recorded spectrum has been possible through
the use of digital storage techniques. To simplify data
handling, an automatic readout unit has been constructed to
be used with an existing memory unit.

The results appear to show a quiet-condition twilight
enhancement due to N_2^+ ions existing in the E region. An
observed band intensity of about 50 rayleighs in the night
airglow would seem to make this possible. An N_2^+ ion abun-
dance of 6.6×10^9 ions/cm^2 above a height of 100 km is
indicated during quiet twilights. No direct evidence was
found to support the hypothesis of F region ionization of
N_2^+ by solar extreme ultraviolet radiation.

During active periods a second layer of N_2^+ ions is
apparently formed in the F region, peaking near 250 km and
decreasing rapidly below this height.

H. M. Sullivan, Lithium, Sodium, and Potassium in the Twilight Airglow,
Ph.D., September 1962.

A birefringent filter photometer has been used to measure
the weaker twilight emissions due to free lithium and potassium
atoms, the twilight sodium emission having been simultaneously
monitored with a wedge photometer. Comparisons of the relative
abundances of Na/Li and Na/K with those found in meteorites
and in sea-water suggest that lithium comes mainly from meteors
while sodium and potassium come mainly from the sea.

A spectacular seasonal variation of the twilight lithium
has been found showing a strong correlation with the occurrence
of the Leonid meteor shower and with two unusual interplanetary
dust particle events, one on November 15-18 and the other on

February 2. Effects of three series of high altitude thermo-
nuclear explosions have been discussed and it is concluded
that, although these seemed to produce a temporary increase
in the brightness of the twilight emission, the large effects
observed were due mainly to natural causes.

The vertical distributions are shown to be roughly the
same for all three elements but the maximum concentration of
lithium occurs at 80 km, approximately 11 km below the sodium
peak, while the maximum concentration of potassium occurs at
about the same height as the sodium peak. A seasonal variation
in the height of the sodium layer has been found, the values
being 88 km in the autumn (August to December) and 93 km in
the spring (January to May).

A possible mechanism for vertical transport of sodium
has been suggested.

A.L. Broadfoot, Intensity of Nitrogen Band Systems in Faint Aurora,
Ph.D., February 1963.

A study is made of the emission in the ultraviolet wave-
length region of the auroral spectrum. The intensity of the
Vegard-Kaplan and second positive band systems of nitrogen
has been measured during several auroral displays.

Variation was found in the population of the $v' = 0,1,$
and 2, vibrational levels of the metastable Vegard-Kaplan
band system. The origin of the population in the upper vibra-
tional levels of the band system is examined. It is shown
that the population arises by cascading of molecules through
the emission of the first and second positive systems of
nitrogen. Variation in population of the vibrational levels
could arise from variation in the relative intensity of the
cascading systems.

A laboratory source of the Vegard-Kaplan band system is
studied and an estimate of the effect of the electronic
transition moment on the band strength has been obtained.
The distribution of intensity among the bands of the system
is shown to be greatly affected by the electronic transition
moment.

The reported distribution of intensity among the v''
progressions of the first positive system in aurora is studied.
It is shown that the distribution is consistent with the
mechanism of excitation by electron collision with the nitrogen
molecule in the ground state. The total intensity of the first
positive system has been generally estimated too high.

Observations were made with a rapid scanning spectrometer.
Improved signal-to-noise ratios were obtained by using digital
computer techniques of storing and summing the spectral records.

G. Chandraiah, A Laboratory Investigation of Vegard-Kaplan Band System
of N_2, M.Sc., April 1963.

A suitable laboratory source of Vegard-Kaplan band system has been designed and constructed. Variation of the electronic transition moment with internuclear distance, for VK bands, is studied and a set of smoothed vibrational transition probabilities has been worked out. The bands are produced in a xenon-nitrogen mixture with an appreciable intensity. The nitric oxide band systems are completely eliminated using barium as a gettering material. Photoelectric measurement of the intensity of the bands in the wavelength region 2600 A to 4000 A has been carried out with a rapid scanning spectrometer in conjunction with a delay line memory unit.

W.F.J. Evans, Auroral Studies with a Multichannel Photometer, M.A. thesis 1963.

The design, construction and testing of a multichannel photometer for rocket-borne auroral observations is described, along with subsequent modifications made for ground-based observations. Calibrated luminosity distributions for auroral forms in the OI $\lambda 5577$, OI $\lambda 6300$, H $\lambda 4861$, N_2^+ $\lambda 3914$ and N_2 First Positive emissions are given. The apparent lifetimes of the $[OI]^1S$ state has been measured in flaming and type-B red aurora as 0.67 ± 0.06 and 0.48 ± 0.06 seconds respectively. The cause of the red appearance of the lower border of type-B red aurora has been investigated. Several proposed explanations have been considered in conjunction with experimental measurements of intensity ratios and time lags in type-B red and normal aurora. In addition, a study of the earth's magnetic field during type-B red aurora was made.

L.E.J. Montbriand, Auroral Hydrogen Emissions, M.Sc. thesis 1961.

Short exposure spectra were obtained from a 2-in. patrol spectrograph which has an f/0.71 grating spectrometer with a slit width of 30A, and a linear dispersion of 310A/mm.

The region of the sky associated with intense hydrogen emissions was defined as the "hydrogen zone". It was found associated with the most southern bright arc or band formation in the sky.

Correlation of forms and hydrogen emissions was attempted.

Diurnal, southward and northward motions of the hydrogen zone are discussed.

The average latitude location of the hydrogen zone throughout a night was found to be magnetically dependent.

Hydrogen emissions were found to occur continuously on the night side of the earth.

Spectra obtained from IGY patrol spectrographs f/0.625 grating spectrometers with 8.2A slit widths, and a linear dispersion of 300 A/mm. were analyzed to determine the exposure

ratios

$$R(H_\beta) = \frac{E(H_\beta)}{E(\lambda 4709)} \qquad\qquad R(H_\alpha) = \frac{E(H_\alpha)}{E(\lambda 4278)}$$

The most probable value of $R(H_\beta)$ was less than 0.2, indicating protons are not the main source of auroral excitation.

Two types of latitude variation of $R(H_\beta)$ for HA are discussed. $R(H_\beta)$ for the brightest aurorae was found to be latitude dependent. At Meanook $R(H_\beta)$ decreases throughout the course of the night, while at Churchill $R(H_\alpha)$ is a minimum at midnight. $R(H_\alpha)$ at Churchill was magnetically dependent.

M. Ahmed, A Study of the Vibrational and Rotational Intensity Distributions in the $\Delta V = -1$ and -2 Sequences of the N_2^+ First Negative System in Aurora.

A study of the low dispersion spectra showed that high vibrational development in the N_2^+ first negative bands is not uncommon as had been supposed. These high vibrational enhancements show a good correlation with the presence of the hydrogen emissions.

Medium dispersion spectra also show that high vibrational enhancements in the N_2^+ ING bands are quite frequent. The vibrational intensity ratios are not a reliable measure of the vibrational temperatures below $1000^\circ K$ as they show very large errors, but the situation seems to be better above $1000^\circ K$.

Atomic lines of the No. 1 multiplet of OII ($3s^4P-3p^4D^\circ$) at 4639Å and 4642Å and the No. 5 multiplet of NII ($3s^3P^\circ-3s^3P$) at 4630Å were observed in the high dispersion spectra. The intensities of the atomic lines close to the (1,3) band peak at 4652Å were computed and were found to be about 40 per cent of the (1,3) band peak intensity at 4652Å.

E.J. Rawson, Rapid Spectroscopic Measurement of Rotational Temperatures of N_2^+ Lines, M.A. thesis 1960. This work has been prepared for publication as Report CR-19, of which the abstract appears earlier in this chapter.

A.E. Johanson, Rotational and Vibrational Temperatures of the N_2^+ First Negative Bands in Aurora, M.A. thesis 1961. This work has also been prepared for publication as Scientific Report CR-10, which has already been abstracted.

R.L. Gattinger, A Study of the Seasonal and Twilight Intensity Variation of the 0.1 Infrared Atmospheric Oxygen Band and Some Observations of the Aurora and Nigh Airglow, M.Sc. thesis 1961.

The spectrometer described by Shemansky (1960) was modified to employ a lead sulphide immersed dewar-mounted cell with a nearly constant sensitivity in the 1.0 - 2.0 μ range.

The O_2 ($^1\Delta g$ - $^3\Sigma_g^-$) 0,1 band emission discovered by Vallance Jones and Harrison (1958) in the evening twilight airglow was observed over a larger range of solar depression angles. The results could not be explained on the basis of a resonance fluorescence in infrared solar radiation.

This 0,1 band at 1.58 μ was found to undergo a strong seasonal variation with a maximum during the winter months and a minimum during the early summer months.

Observations of the OH($^2\pi$ - $^2\pi$) system present in the night airglow indicated that the intensity ratio of the 4,2 band to the 5,3 band was approximately 1.4.

A photometer was constructed to record intensity variations of the N_2^+ 3914 Å auroral emission in the field of view of the infrared spectrometer during the recording of auroral spectra. The results of auroral observations indicated the relative brightnesses of the emissions arising from the 0,0 band of the Meinel N_2^+ system at 1.109 μ, the 0,0 band of the N_2^+ First Negative system at 3914 Å, and the emission at 1.04 μ to be 2, 1.3, and 1 respectively.

D.E. Shemansky, A Study of Higher Resolution Spectra of the Airglow and Aurora From 1.4 μ to 1.65 μ, M.Sc. thesis 1960. The material in this thesis forms the basis of Scientific Report CR-8.

Chapter 9. CONCLUSIONS

During the period covered by this contract substantial advances have been made in knowledge of the occurrence and height distribution of alkali metals in the upper atmosphere as a result of the twilight observations. The arrangement for simultaneous routine measurements of sodium in the twilight from Christchurch, New Zealand as well as from Saskatoon has provided an opportunity to study the correlation between observations in the two hemispheres in great detail. Similarly the establishment of a continuous series of observations of lithium concentrations in the upper atmosphere provides a valuable new tool for the study of the natural seasonal variation and the artificial injection of this element into the atmosphere through high altitude nuclear explosions for rocket releases. It is planned to maintain continuous observations of lithium and sodium, and to commence continuous observations of potassium.

The problem of the twilight and dayglow atmospheric infrared bands of oxygen, although by no means solved, seems susceptible to several promising lines of investigation. This is in contrast to the situation three years ago when there seemed to be little chance of making further progress. Although this will probably lie outside the scope of the present contract or its successor, it is planned, as part of the optical research program of the Institute of Upper Atmospheric Physics, to attempt to measure the height distribution of the dayglow emission with a rocket-borne photometer. It is hoped to develop a photometer which may also be useful for balloon or aircraft work.

In the field of auroral spectroscopy, our attempts to obtain a complete high-dispersion spectrum have not yet been completely successful. We feel that it would be more profitable to concentrate on a program of measurements of accurate relative and absolute intensities

using photographic and photoelectric techniques with the eventual object of producing a photometric atlas of the auroral spectrum at medium dispersion. The observations of the infrared spectrum in the photoconductive region should be integrated into this scheme.

The object of the patrol spectrograph program will be to set up the chain of stations from Saskatoon through Flin Flon to Churchill to obtain a full understanding of the relation of proton impact excited emissions to aurora. This chain would constitute a permanent facility from which data would be available to correlate with satellite or balloon observations.

Further knowledge of the infrared night airglow may arise from the operations of the infrared spectrometers and of the Michelson interferometer. A specific design has been evolved now for an instrument to measure OH temperatures on a routine basis, and it is hoped to commence construction of this instrument this year. The Contract continues to provide support for the training of workers in the field of upper atmospheric physics. Dr. J.F. Noxon has left the group and is now carrying out a research program at the Blue Hill Observatory of Harvard University. Three students have graduated with Ph.D.'s and nine with M.A.'s or M.Sc.'s. The present activities of these recent graduates are of some interest and this information is tabulated in Appendix A. It is also of interest to note that in addition to the program initiated at Harvard by Noxon, Dr. H.P. Gush, who did his original work on the infrared spectrum of the night airglow in the 1.0 to 2.0 μ region here under the support of this series of Contracts, is now carrying out important work in this field using Michelson interferometers at the University of Toronto. Dr. G.G. Shepherd, who also began his research under the support of the predecessor of this Contract, is now heading another research group at

the University of Saskatchewan, carrying out optical measurements of upper atmosphere emissions. These examples show that the benefits accruing from the support afforded by this Contract considerably exceed the value of the actual research results listed in these final reports.

Chapter 10. ACKNOWLEDGMENTS

Many persons in many capacities have contributed to the work reported here. In most cases the contributions of students and staff of the Department of Physics and the Institute of Upper Atmospheric Physics are recognized in Chapter 8. Work not yet written up for publication has been done by E.J. Fjarlie, while important contributions have been made by H.J. Koenig, G. Luimes, A.H. Cox and F. Rittmann. The general cooperation of the professional and secretarial staff of the Institute of Upper Atmospheric Physics and the Physics Department is much appreciated.

APPENDIX A

Present Locations of Former Staff and Graduate Students
Supported by Contract AF19 604-7265

Dr. J.F. Noxon, Blue Hill Observatory, Harvard University

Ph.D. Graduates

Dr. E.A. Lytle, Canadian Armament Research and Development Establishment, Valcartier, Quebec

Dr. H.M. Sullivan, Observatoire de Meudon, S. et O., Paris

Dr. A.L. Broadfoot, Kitt Peak National Observatory, Tucson, Arizona

M.A., M.Sc. Graduates

Mr. J.K. Walker, Dominion Observatory

Mr. I. Maartense, Eaton Electronics Laboratory, McGill University

Mr. A. Johanson, Defence Research Northern Laboratory, Fort Churchill, Manitoba

Mr. L.E.J. Montbriand, Defence Research Northern Laboratory, Fort Churchill, Manitoba

Mr. M. Ahmed, Institute of Upper Atmospheric Physics, University of Saskatchewan

Mr. G. Chandraiah, Institute of Upper Atmospheric Physics, University of Saskatchewan

Mr. W.F.J. Evans, Institute of Upper Atmospheric Physics, University of Saskatchewan

Mr. D.E. Shemansky, Institute of Upper Atmospheric Physics, University of Saskatchewan

Mr. E.G. Rawson, Physics Department, University of Toronto

AF Cambridge Research Laboratories, Bedford, Mass.
Geophysics Research Directorate. BASIC RESEARCH ON
AURORA AND AIRGLOW, by D.M. Hunten and A. Vallance
Jones, April 1963.

pp.   AFCRL-   Unclassified Report

Equipment for optical studies of the aurora and airglow
developed at the University of Saskatchewan is described.
Observations of the twilight emission of sodium, lithium
and potassium, carried out from 1960 to 1963 are reported.
The twilight observations of lithium show clearly the
effect of high altitude nuclear explosions. Spectroscopic
studies have been made of the Vegard-Kaplan and second
positive bands of N_2 and of H in the aurora. A temper-
ature profile for the atmosphere from 95 to 170 km has
been obtained from the N_2^+ bands. The infrared atmos-
pheric bands of O_2 have been studied in the twilight and
day airglows.

UNCLASSIFIED

1. Hunten, D. M.
and A.
Vallance
Jones